Large Eddy Simulation of Sediment Transport in the Presence of Surface Gravity Waves, Currents and Complex Bedforms

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LONG-TERM GOALS

Our long term goal is to develop numerical simulation techniques for generating accurate predictions of sediment transport in the coastal zone at horizontal scales of 10s of meters or less.

OBJECTIVES

Our earlier work has produced accurate hydrodynamics and sediment transport dynamics. Our first focus now is on nonhydrostatic motions and transport on scales of the order of meters and in the presence of waves and currents. Our second focus is to use a fully three-dimensional, nonhydrostatic, free-surface code to study both laboratory scale and field-scale motions and transport related to the burial and unburial of cobbles/mines. We seek to produce at the same time a sediment transport code without the typical parameterizations and approximations used in codes applied at the scales of kilometers.

APPROACH

The Large Eddy Simulation [LES] code of Zedler and Street, 2001, is used in this work. [N.B.: This paper produced with support from this grant was awarded the 2002 Hilgard Hydraulic Engineering Prize of the American Society of Civil Engineers.] The code solves the volume-filtered Navier Stokes equations for the three components of velocity, a Poisson equation for the pressure, and an advection diffusion equation [with settling term] for the sediment on a non-orthogonal, boundary-following grid. The code was extended to handle field-scale and rough-wall flows with Reynolds number Re ~ 600,000 by implementation of a log bottom-boundary-condition. The subfilter scale terms that arise from the volume filtering are represented by a mixed subgrid-scale model. The equations are discretized in time with a semi-implicit method and in space with second order differencing and solved with a fractional step/projection method.

For the prototypical vortex ripples, we employed monochromatic oscillatory flow over the ripples with the driving pressure gradient signal (normalized by the density) being a monochromatic sine wave with amplitude of 0.75 m/s^2 and period of 10 s. The sediment transport over the *real* rippled bedform topography and in *real* flow conditions was simulated also in three dimensions and time. For the field conditions, the rippled bedform and flow conditions were derived directly from Prof. T. Stanton's field measurements made 12 km offshore from the FRF shoreline facility and seaward of the breaker zone in the bottom 0.36 m of the water column at Duck, N.C., during SHOWEX. The simulated velocity field was driven in both the cross-shore and longshore directions with a pressure gradient, determined from the balance between the local oscillatory pressure gradient and local fluid acceleration at 0.36 m from the bed. Representations of the rippled bedforms measured in the field were obtained by first removing the mean cross-shore slope, then augmenting the domain appropriately to form a periodic shape. A simpler grid was also formed by using a longshore-averaged description of the cross-shore bedform to create a grid that varied in the cross-shore direction only.

Finally, we have developed a plan for simulating the burial and unburial of mines, employing the boundary-element method of Grilli [see, e.g., Grilli, et al., 2001] to drive the boundary conditions of our code which will simulate the actual transports about the mine and the attendant bed erosion.

WORK COMPLETED

Three major tasks were accomplished. First, for flow over vortex ripples [see our previous report] we have completed our analyses. Second, methods for emulating the flow and topography for field conditions were developed, as described above. Third, simulations of some SHOWEX data were conducted and analyzed.

RESULTS

The prototypical vortex ripple shape employed in this study was a straight-crested sinusoidal ripple with a grid [with regular spacing in the horizontal directions and exponential stretching in the vertical] was created and contained 258 x 50 x 98 grid points to represent a 4.5m L x 0.65 m H x 1.0m W domain. Only the bottom 0.65 m of the water column was simulated.

The transport patterns over the vortex ripples have been well documented by field, laboratory and numerical simulation studies. All of the basic flow and sediment transport patterns are reproduced in our simulations: As the flow begins to speed up towards its maximum magnitude in either direction, a spanwise vortex begins to form in the lee of each ripple. This vortex traps sediment that is picked up on the ripple upslope (due to large shear stresses there) and hurled over the ripple crest and into its lee. As the flow slows down towards zero velocity, some of this trapped sediment is lost due to settling but some remains in suspension and the strength of the vortex intensifies relative to the small neighboring velocities. The near-bed velocities, which have already turned around due to the favorable pressure gradient, carry the cloud of sediment remaining in suspension over the ripple crest. This represents the primary sediment entrainment mechanism over vortex ripples. Figure 1shows the sediment concentration over a vortex ripple during flow reversal. The streamwise-vertical plane velocity vectors are shown on the channel center plane where a spanwise vortex has just been ejected off the bottom and trapped some sediment. The plane perpendicular to the main direction of the flow shows the

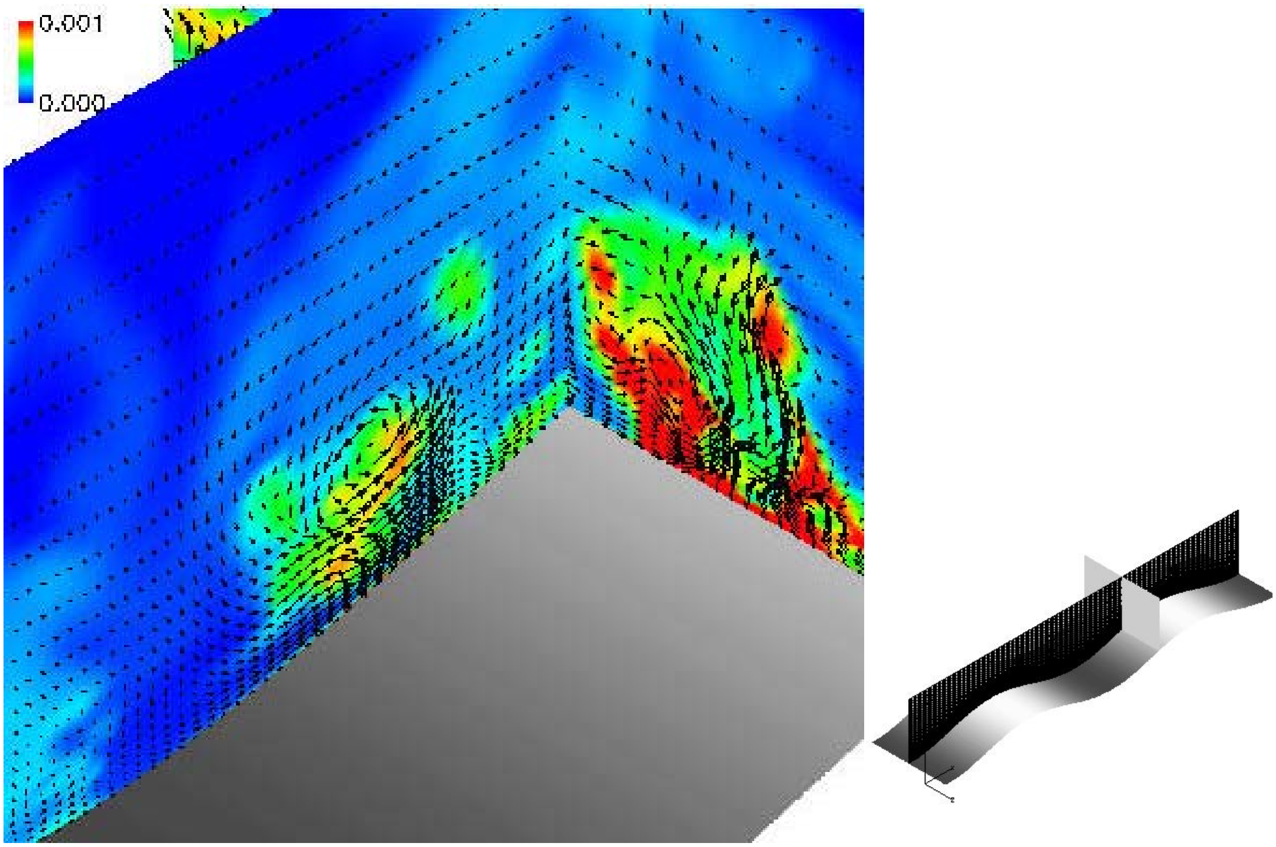

Figure 1. Sediment transport over vortex ripples of 2.25 m wavelength and 0.1125 m amplitude (the ripple wavelength to height ratio is 1/10, the cutoff for vortex ripples). Insert shows ripples and planes on which sediment concentrations [mass concentration fraction, scaled per color bar] and velocity vectors are displayed. Only one-quarter of the velocity vectors are displayed.

spanwise-vertical plane velocity vectors, which show the signatures of the eddies that typically form in the flow during flow reversal. Sediment concentration is represented by the color contours. In addition, as mentioned in the Approach section, two simulations of the Duck, N.C. data have been performed—over straight-crested ripples and over the three-dimensional ripples. These all had the same particle size of 165 μm. An additional case over the three-dimensional ripples was run with a smaller particle size of 125 μm because this better reflected the median particle size present at the site. For brevity, only the most physically relevant results—those over the three-dimensional ripples—are shown below.

Excellent agreement between numerical results and field data was obtained for the horizontal velocity components in the cross-shore [U] and longshore [W] directions. Figure 2 plots raw data against simulation results for different heights above the bottom at the location of the probe, each dot representing an instantaneous measurement extracted at the location of the probe in the computational domain plotted against its instantaneous field measurement. At all depths, the r^2 correlation value is above 0.75. The vertical velocity measurements correlated less well in time, but velocity magnitudes agreed reasonably well. A mean negative bias was present in the field data when burst averaged and we are still examining its cause; when it is subtracted from the data, the comparison with our data improves.

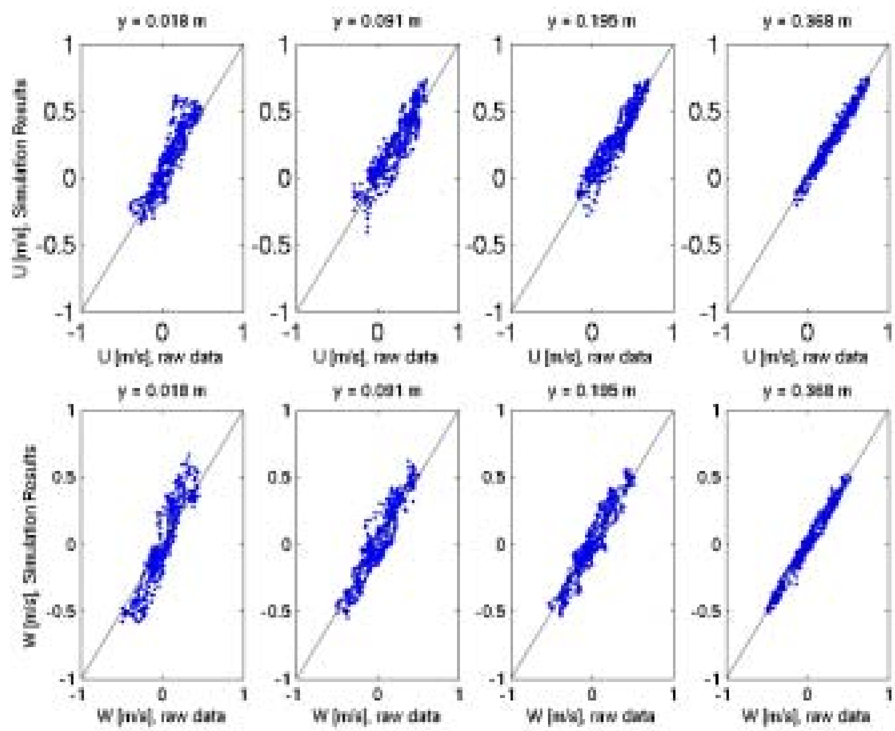

Figure 2. Raw SHOWEX field data versus simulation results for cross-shore U and longshore W velocities at various elevations above the bed.

Computed sediment concentrations also agreed reasonably well with field measurements—in general, within a factor of 2-3. Figure 3 illustrates the data at the probe as a color contour plot; it is clear that the sediment suspension events have been well resolved in time at the probe's location, of note those occurring between 88 and 94 seconds. Although the near-bottom computed concentration values are over-predicted, the model predicts the timing of these detailed suspension events quite well. Simulation with different particle sizes present in the measured samples reveal a range of patterns, suggesting that a complete simulation with graded sediments is needed to accurately represent the measured fields. Such simulations are underway.

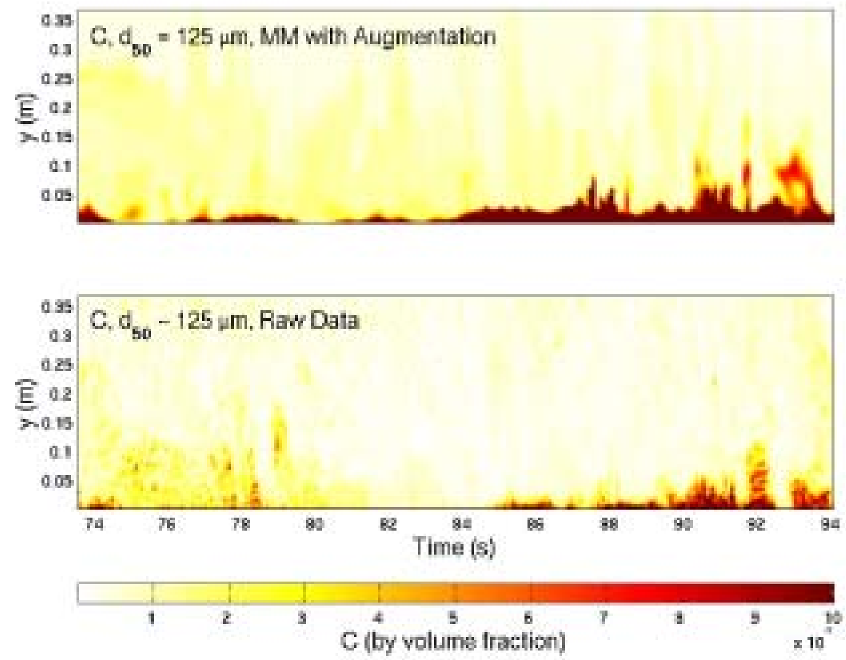

Figure 3. Contours of the time evolution of sediment concentration profiles. Above: Simulation results; Below: Raw Data.

We will extend this methodology to simulations of field data collected by Prof. Timothy Stanton [NPS] in Monterey Bay. In addition, the data above will be analyzed further to establish more links between the underlying three-dimensional flow and the sediment transport events measured at the probe.

IMPACT/APPLICATIONS

The results above demonstrate that Large-Eddy Simulation provides a reasonable physical description of the sediment transport that occurs over ripples and under waves at large Reynolds number and at field scales.

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PUBLICATIONS

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